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A REVIEW OF EMPTY FLOWS AND FLEET MANAGEMENT MODELS IN FREIGHT TRANSPORTATION

by

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ABSTRACT

The transportation of freight, by any mode, usually generates a significant number of empty vehicle movements. Understanding and controlling this phenomenon is important for all levels of transportation and logistic system planning. In this paper, we propose a taxonomy of empty vehicle flow problems and models and review the existing literature on the subject. Major research trends and perspectives are identified and the advantages of a hierarchically integrated approach for the simultaneous management of empty and loaded freight vehicle movements are discussed.

Key words : empty vehicle movements; freight transportation; logistics; distribution and transportation systems planning, fleet management.

RÉSUMÉ

Le transport de marchandises génère une proportion importante de mouvements de véhicules vides. La compréhension et le contrôle de ce phénomène ont un impact considérable sur tous les niveaux du processus de planification des systèmes logistiques et de transport. Après avoir proposé une classification des problèmes et modèles reliés aux déplacements de véhicules vides, nous analysons l'ensemble des articles de la littérature scientifiques publiés sur ce sujet. Les tendances et perspectives de la recherche dans ce domaine sont identifiées et nous discutons des avantages d'une approche hiérarchiquement intégrée de la gestion des déplacements des véhicules vides et pleins combinés.

Mots-clés : mouvement de véhicules vides; transport des marchandises; logistique; planification des systèmes de distribution, gestion de flottes de véhicules.

INTRODUCTION

The transportation of goods is an essential economic activity involving a large number of complex operations for the shipment of multiple products using vehicles of different types and various modes, through networks of a complicated structure.

A vast literature exists on the many aspects of the problem of how to design and operate freight logistics, transportation and distribution systems. Research has addressed strategic or tactical planning issues as well as operational activities. For example, an entire conference sponsored by the U.S. National Science Foundation was recently devoted to the state of the art and research opportunities in all aspects of transportation research [12]. Up to date research books have also been published in the areas of transportation planning models (e.g. Florian [46]) and logistics (e.g. Handler and Mirchandani [67]). Methods for distribution systems planning have been analyzed by, for example, Geoffrion and Powers [56] and Dejax [35]. Models for freight transportation have been reviewed by Assad [1], Friesz, Tobin and Harker [54], Harker [69] and Crainic [17]. Operational models for the routing and scheduling of vehicles and crews have been surveyed by Bodin et al. [10] and Rousseau [129], respectively.

Most of these reviews address planning or operational problems of loaded vehicle freight transportation. The important issue of empty travel in fleet management has received, however, little general attention [140], although empty travelling is often done before, after and sometimes during loaded trips. Yet, there are many difficult problems, with significant impacts upon the operational and economic performance of the system, related to the distribution and movement of empty freight vehicles in all modal and intermodal transportation systems.

Researchers and practitioners generally agree that a significant amount of all miles travelled are carried out by empty vehicles. In the small network of the Swiss Federal Railways alone, 12 000 empty freight wagons of 70 types have to be allocated each day to and from 850 stations [77]. In the U.S. rail system, it is estimated that for 40% of the time of the average car cycle, the car is empty [104]. In the trucking area, a detailed survey carried out in Great Britain estimated that about one third of all goods vehicles on the road at any time are running empty. For heavy commercial vehicles, this apparent wastage amounted to 1 400 million pounds sterling and contributed significantly to the perceived truck nuisance on the quality of life in both the city and in the countryside [26]. In the U.S. motor carrier industry, approximately 12% of total miles travelled by large truckload and less-than-truckload companies are reported empty [122]. In the area of container transportation, Dejax, Durand and Servant [37] describe a large European system in which 40% of total transportation costs for 200 000 movements each year was due to empty trips of various kinds.

This vast amount of empty travelling has numerous and interwoven causes, such as government regulations, intercompany agreements, vehicle specialization and interregional commodity flow imbalances. Thus, as empty movements generate costs but no revenues, the empty freight transportation problem is concerned with the reduction of empty vehicle traffic, while improving or, at least, not encroaching on the efficiency of loaded travel operations.

The purpose of this paper is to review and bring together the work done in empty vehicle transportation either as a main subject or as a subproblem of a larger transportation study. We also aim to draw attention to interesting research trends and problems in the domain, as well as to suggest a hierarchically integrated approach to the problem of simultaneously managing empty and loaded freight vehicle movements.

The paper is organized as follows. Section 1 proposes the criteria used to classify the problems and models on empty freight vehicle travel. Sections 2 and 3 review the operational and policy models, respectively. Section 4 concludes the paper and summarizes current research trends.

Models developed for each class of problems are presented chronologically. We thus emphasize the methodological evolution among successive approaches. In particular, we point out the major innovations as well as the current state and trends of research.

1. A TAXONOMY OF EMPTY FLOW PROBLEMS

Several criteria may be used to classify the numerous and often very diverse research works which address the empty freight vehicle movements issue, either as their main subject or as a sub-problem of more general transportation or logistic planning problems.

Traditionally, physical (e.g. the transportation mode), or methodological (e.g. simulation versus optimization models) criteria have been used. For our part however, while acknowledging the importance of such factors for the precise definition of both problem and solution, we believe that a more fundamental discriminating characteristic is the scope and breadth of the study. We therefore distinguish between :

a) policy models that cover long or medium term, strategy oriented, planning problems; this includes demand forecasting, fleet sizing, national and regional planning, carrier service network design, depot location and logistic system design;

b) operational models that address shorter term problems such as inventory control of the stock of empty vehicles, the determination of origin-destination empty flows, and the dispatching of empty and loaded vehicles; here, one distinguishes between real-time approaches and models that address planning issues even if over very short time horizons.

This classification , which extends that proposed by Dejax, Bine and Gozlan [36] and parallels that of the decision levels in the classical industrial planning process, presents the advantage of clearly identifying the class of problems studied, its scope, width and impact, as well as of casting an often revealing light on the chosen methodology. It also suggests a hierarchical approach to the problem of managing empty flows in freight transportation that we discuss in section 4.

Of course, this is not a rigid classification. There are models that, depending on the application context, may be classified in either category. In this review we indicate such occurences.

Once the fundamental nature of the problem has been specified, several additional criteria are useful for a precise definition of the problem and of the solution methodology.

The problem-defining criteria are:

a) Type of flow : the problem is concerned exclusively with the flow of empty vehicles or considers, either concurrently or sequentially, both empty and loaded vehicle movements.

b) Transportation mode : the problem considers either one mode of transportation (e.g. rail, truck, navigation, container, etc...), or several modes are allowed (multimode problems). Historically, the numerous models developed for rail have served as an inspiration and starting point for the other modes. Several important similarities notwithstanding, the transportation mode introduces, however, specific requirements which are reflected in the models designed for these modes. An interesting variant occurs for the rail and container cases : several different interacting companies but one single mode. We call these multicarrier problems. Note that we did not find any published research relative to sea or air empty vessel management or fleet sizing.

c) Fleet homogeneity : the problem may treat either a homogeneous fleet or several types of vehicles (they may totally, partially or not at all substitute for one another) that have to be managed concurrently (multicommodity problems). Note that, when vehicle substitution is not allowed in a nonhomogeneous fleet problem, the case usually decomposes into several homogeneous fleet subproblems.

d) Type of company : discriminating between the freight carrier and the industrial firm which operates a fleet of vehicles (owned or or rented) either for interplant or intraplant transportation, for distribution of products (to warehouses or clients), or for provision of supplies (parts, raw materials, etc.).

Differences may exist, at the operational level, between transportation problems of the industrial firm and the freight carrier. They are relative to cost and service objectives, fleet size, number of terminals and clients, demand forecasting, repetitivity of routes and shipments, etc. However, for a given problem size, the fundamental structure of the models and solution techniques developed for both cases are the same, even if they may be applied differently, depending on the context. Similarly, policy defining questions may be addressed in a different context for the industrial firm and the freight carrier. But similar modeling methodologies and algorithms are used. Actually, some of the research which we analyzed for this review has been applied to industrial problems, while much of it has been applied to freight transportation firms, but the formulations did not emplicitly take these difficulties into account.

The methodology defining criteria distinguish :

a) modeling assumptions :

- time domain : the problem may be static, considering an "isolated" or typical planning period, or dynamic, where the problem has to be solved over several contiguous time periods;
- deterministic or stochastic hypotheses on supply and demand or network performance mesures (travel time, for example).

b) modeling approach :

- algebraic formulation for subsequent optimization with mathematical programming techniques;
- analytic stochastic models such as queueing models;
- simulation models (e.g. Monte Carlo).

c) solution techniques :

- mathematical programming (linear, nonlinear, integer, etc.) optimization;
- network algorithms;
- stochastic optimization;
- simulation.

2. OPERATIONAL MODELS

The purpose of operational models is the efficient management of a given fleet of vehicles : i.e. to decrease the cost of empty travel while satisfying the demand adequately (e.g. avoiding delays, etc.).

The problems are usually defined on a network over which loaded and empty movements take place. At some nodes of the network, representing yards, terminals, depots, etc., demands and supplies (from loaded movements and external sources) of empty vehicles are specified (see section 3.2).

The models address either the management of the inventory of empty vehicles at terminals of the network or the allocation/dispatching of empty vehicles to certain origin-destination (O/D) pairs to satisfy the demand.

The problem and methodology defining criteria specified in the previous section are used to create the subdivisions of this section.

Note that although we use the terminology "empty vehicle allocation," (Powell [122]) some authors prefer the term "vehicle distribution". We believe that "allocation" is best because it not only avoids the "logistic" connotations of "distribution", but also reflects the real decision to assign/allocate a certain number of vehicles to a specific O/D trip. Note also that models which actually route and schedule vehicles on their trips are beyond the scope of this paper. We refer the interested reader to the recent and thorough review of Bodin et al. [10].

2.1 Inventory management of empty railroad cars

Railroad cars are allocated depending on the existing supply of empty cars and their demand at classification yards or railroad terminals. One of the problems addressed by researchers has therefore been that of maintaining an adequate supply of empty cars at the network terminals.

Philip and Sussman [117] propose such an inventory model. Following the work by Philip [116], they design a discrete event simulation model to determine optimum inventory level for a single terminal area as a function of daily supply variations, daily demand variations, and the cost of holding a car in a terminal waiting for loading as compared with the cost of having no car available to satisfy the shipper demand. The inventory model approach is presented as an alternative to the classical transportation optimization methodologies developed earlier by White and Bomberault [148] for empty car allocation problems (see section 2.2.1).

A first attempt to use the model to evaluate the performance of a real railroad terminal area indicates that excessive inventories are maintained in surplus terminal areas. The applicability of the model to a real railroad operating situation is also demonstrated. However it was possible to test the model only for a surplus terminal area.

In their conclusions, Philip and Sussman insist on the impact that supply and demand variability has on the number of cars needed in the inventory of a given terminal. They indicate therefore, that such a single terminal inventory management model should be part of a more comprehensive set of models that could be used as a tool by managers seeking to balance empty-car inventories over an entire network.

The research of Mendiratta and Turnquist [105] represents precisely such a successful attempt at building a general empty car inventory management model over an entire railroad network. Mendiratta and Turnquist view the lack of coordination between decisions made centrally for the whole railroad and decisions made locally at individual terminals as the main reason for empty-car distribution problems and, consequently, apply to the rail case the methodologies first developed by Baumol and Fabian [7], Lasdon [96], and Jennergren [81] for the optimization of decentralized systems. The resulting model incorporates interacting submodels - the network model and the terminal model - each representing the activities performed at the corresponding level in the railroad system: central decision making at coorporate headquarters is concerned with movements over the total railroad network, while the inventory-sizing decisions are made at each individual railroad terminal. Decisions are made at each level (corporate and terminal), while the coordination between the two levels relies on a price mechanism. The objective of the system is to maximize profits for the railroad subject to the constraints imposed by available empty cars, shipper demands for empty cars, and institutional requirements. In order to achieve system optimality, there is an iterative exchange of information between the network model and the terminal model. The network model determines internal transfer prices (dual variables) for empty cars that are then input to the terminal model; the terminal model uses these prices to determine orders of release of cars. These orders and releases

are then input back to the network model for recomputation of transfer prices. Iterations continue until the results of the two component models are consistent and the internal transfer prices between the two models reflect the opportunity cost of cars. The precise derivation of the form of the price schedules of the network model may be found in Mendiratta's doctoral thesis [104]. The model is formulated as a linear programming optimization model and solved by Dantzig-Wolfe decomposition [96]. The terminal model is an inventory-control formulation that incorporates stochastic demand and lead times for the delivery of empty cars. It differs from the inventory control model of Philip and Sussman [117] only in the details of the formulation, which is described in Mendiratta [104].

An important aspect of the model is that it functions even when there is an overall shortage of empty cars in the system. By incorporating price information and by constructing the network model to emphasize decomposition, Mendiratta and Turnquist have overcome two of the difficulties of earlier network optimization models of Feeney [42], White and Bomberault [148] and Misra [108] that impose complete centralization of decision making and do not function well when cars are in short supply.

The model can be used as a policy evaluation tool by railroad central management and as an operational tool for the daily distribution of empty cars by terminal personnel. Tests using data from a U.S. railroad indicate that the model leads to distribution decisions that reduce empty-car miles, empty trips, and empty-car days without reducing the percentage of demand satisfied.

2.2 Empty vehicle allocation

Historically, the allocation of empty rail vehicles has received

much more attention than the corresponding problems in other transportation modes. This trend continues even today, despite growing interest in motor carrier and multimode container problems. In addition, work that was initially done for the rail mode has often been adapted and expanded for other modes. An important part of this section is therefore dedicated to the rail mode.

2.2.1 Rail carrier

Deterministic approaches

Following the breakthroughs of the 50's and the developments of the 60's in linear programming (L.P.), network modeling and algorithmic techniques, a large number of studies were carried out during the late 60's and 70's concerning the application of these methods to the rail freight car allocation problem.

These optimization models were used to "optimally" distribute empty cars according to specified allocation rules and goals. Several such models were developed for and sometimes used by railroad companies (Baker [5], Mendiratta [104]), as well as by national planning agencies (Miller [106], [107]).

One of the first and most straightforward formulations is that of Misra [108] which minimizes, over a specified period, the total cost (in car-hours) of countering the known imbalances of empty cars of a homogeneous fleet at the nodes of a railway division network. The transportation algorithm (Ford and Fulkerson [50]) and the Simplex algorithm (Dantzig [27]) for the route capacitated case, are presented as solution methods. The stochastic nature of the demands and supplies of empty cars is acknowledged and either daily optimizations or the utilization of averages, are proposed as solutions. The possibility of stochastic modeling of demands

and supplies in conjunction with sequential application of L.P.'s, is also mentioned.

The Louisville and Nashville Freight Car Scheduling Model (Leddon and Wrathall [99], Wrathall [151], Association of American Railroads [2]) and the Southern Railway's Optimal Flow Rule Model (see Baker [5]) are also static linear transportation models for known supply and demand of empty cars of a homogeneous fleet. Standard simplex codes were used to solve the models which received, at the time, very favorable appraisals.

White and Bomberault [148] address the same problem but add the time perspective via a space-time diagram which schematically represents the various paths that cars may travel to reach their proper destinations at a specified time. This structure is used to generate a network over which the total cost of moving the cars is minimized. The fleet is again homogeneous, while demands and supplies are known. An adaptation of the out-of-kilter algorithm (Ford and Fulkerson [50]) is used to solve this transshipment problem. The introduction of a dynamic time domain represented a significant contribution to the field and the work of White and Bomberault was the seed of numerous developments in empty vehicle allocation models for all transportation modes.

In conjunction with a study of the dynamics of freight car distribution systems, Ouimet [111] also proposes an empty car distribution model along the same general lines as White and Bomberault : space-time (capacitated) network, homogeneous fleet and an objective to fill current and predicted demand while minimizing service delays (as a general goal), empty car-miles and the number of empty cars held in yards (via storage arcs introduced in the time-space network) by an out-of-kilter algorithm. Ouimet emphasizes the importance of having correct estimates of demands and supplies and suggests running the model at each period while updating the

forecasts. This approach has been used by the Canadian Pacific Railroad as a guide in the system-wide allocation of its freight cars (Baker [5]).

The Swiss Federal Railroad's (SBB) Distribution Model (Herren [76]) is also an optimization model aimed at maximizing demand satisfaction and minimizing costs related to switching operations and empty car kilometrage. The SBB model considers a heterogeneous fleet with substitution possibilities and some other, company specific, limiting conditions. This is achieved by representing the empty car distribution plan as a minimum cost flow model on a space-time network where each node corresponds to a specific car type on a specific train departure (or arrival) from (to) a particular yard. Arcs are introduced into the network to represent switching operations, car substitutions and train movements. Due to the size of the Swiss network, the model could be solved by a modified out-of- kilter algorithm. Results indicated the possibility of reducing the fleet while maintaining full demand satisfaction. There was also a substantial reduction in empty car kilometrage and associated costs.

The whole package was intensively tested and went into operation, twice each working day, in 1976. Herren [77] reports that the SBB obtained satisfactory results with the model.

That problem size is a determinant factor in the success of the SBB model is emphasized by the work of Hein [73], [74] for the German railways (Deutschen Bundesbahn-DB). The problem is very similar to that of the SBB, with car substitutions between different car types, following strict rules, being an important factor. Hein first examines a transshipment formulation combined with an out-of-kilter algorithm. This approach proves, however, to be impractical due to the size of the problem. Hein also questions the pertinence of using exact algorithms when there is significant uncertainty in the data. He then uses an heuristic, first suggested by Gigon and Schlaepfer [57], which transforms the problem into a transportation problem

on a bipartite graph where classes and groups of classes of cars are at the nodes and costs are approximated by shortest paths algorithms. No real application results are reported.

Recently, Fernandes Grain and Figliatti de Sinay [43] proposed, in the Brazilian context, an L.P. formulation of the static empty vehicle allocation problem for a homogeneous fleet with known demands and supplies, which maximizes the profitability of the system. The model is solved with a standard simplex algorithm. This approach is very similar to the earlier work presented in this section and, unfortunately, the authors do not seem to be aware of the most recent advances in the domain.

All these papers represent the main-stream of linear programming models of the empty vehicle allocation problem for one individual rail carrier : either a transportation or a transshipment formulation solved by general (simplex) or specialized (transportation, out-of-kilter, etc.) algorithms. These deterministic models are still very much used today, either on their own, or as part of more sophisticated formulations, even if, as seen in a later section, the current trend is toward explicit consideration of stochastic elements while modeling. We encounter, for example, these techniques in the particular case of the "pool concept". Meanwhile, several other approaches have been explored for the rail carrier case.

Decision Systems Associates Inc. [33], [34] developed, under the sponsorship of the U.S. Federal Railroad Administration, a multiobjective network optimization model for optimal freight car allocation which was meant to supplement a real-time freight car management information system. Several objectives (maximize accomodation of shipper demands, minimize operating costs, minimize delivery delays, maximize the return of foreign cars, minimize car substitution) were defined and prioritized so that "the optimal solution to each objective constrained the space of feasible solu-

tions for each lower-ordered objective". DSAI developed a six step iterative process that integrates primal-dual algorithms and a nonlinear optimization method. In the event of a shortage of cars, assignments are made first to orders with the highest priority. The model was validated with data from Southern Pacific's Total Operations Processing System, the results indicating that significant benefits could be obtained if the computer based model was used instead of the manual method.

DSAI's model requires a sophisticated information retrieval system and an accurate method for forecasting supply and demand. This, especially for the second requirement, is a common characteristic of all models reviewed herein.

Heuristics have also been proposed, especially when the methodology was aimed at rationalizing and closely reproducing manual techniques. Thus, Leal [98] proposes a heuristic algorithm to reduce empty travel when the cars are generally sent back to the origin of the loaded movement. This is accomplished by searching in the transportation plan for loaded movements that are on the return route of an empty car and that could therefore be accomplished by that car. The idea seems interesting for certain situations such as captive fleet or linear rail networks. No experimental results are presented, however.

Stochastic approaches

The significant impact of the variability of demand and supply and the consequent importance of good forecasting techniques has been widely acknowledged in the literature. In section 3.2, we review work dealing with the forecast of future demand and supply. Another important research avenue, however, is the inclusion of uncertainties in the allocation model itself.

The first comprehensive effort in this direction was made by Turnquist and Jordan (Jordan [83], Turnquist and Jordan [143], Jordan and Turnquist [86]. This resulted in MOV-EM, a network optimization model for empty freight car distribution (Turnquist [141]). This research is innovative in two ways. First, while aiming to maximize the profits, the authors explicitly consider and integrate several cost items : revenue from filling orders, costs from holding cars unused at yards, stockout costs from not filling orders and costs of moving cars between yards. Second, Turnquist and Jordan build their model around the stochasticity of supply, demand and travel times.

The model uses a space-time network whose nodes are yard locations at specified times, while arcs represent car movements between yards and car holdings between periods at yards. The model maximizes an objective of expected profitability as determined by known and forecasted supplies and shipper demand for empty cars (of several types, at various locations on the network), travel times and costs revenues, holding costs and stockout costs. It determines, using current information and forecasts, the best decision for the current period and anticipates future distribution decisions. As time passes, additional information becomes available and the model may be re-run for the new "current" period using the updated data. The means and variances of future supply and demand (at each location and period, for each car type) as well as the mean and variance (from an assumed negative binomial distribution) of the travelling times between each pair of yards are assumed known. Turnquist [141] presents computing methods for some of these quantities, as well as details on how the stochastic equations that integrate them are developed. The model is a nonlinear optimization problem with linear decomposable constraints similar to a (maximizing) stochastic transportation problem that Cooper and LeBlanc [13] solved using a Frank-Wolfe algorithm (Frank and Wolfe [51]).

Turnquist and Jordan also developed a Frank-Wolfe algorithm for their problem but remark that since their objective is not necessarily concave, the algorithm has to be considered a heuristic. They report, however, that computational experience has shown it to be very effective.

To our knowledge, this model has not yet been implemented at any rail company. We consider, however, that the work of Turnquist and Jordan represents a milestone in the development of accurate empty freight vehicle allocation models through the introduction of stochastic optimization models and technics to the field of fleet management problems.

Hybrid approaches

Rail companies have, for a long time now, used simulation models to assess the overall impact of operating policies and procedures. Simulation models are generally very detailed representations of yard or network structures and operations and, as such, enjoy high credibility in the industry. Baker [5] and Assad [1], among others, review simulation models used in the rail industry. These models however, are also generally very expensive (in terms of analyst time and computer space and effort) to implement and run, besides being unable to suggest new policies or to optimize old ones.

Ratcliffe, Vinod and Sparrow [128] present an interesting hybrid approach which tries to integrate and profit from the advantages of simulation, linear programming and stochastic linear programming.

The authors' aim is to increase freight car utilization via an increased number of revenue trips accomplished in a given time period. They do this by prepositioning empty cars closer to the expected demand, thereby decreasing the final distance travelled and increasing the readiness of the system to deliver empty cars where and when needed. The supposedly known net supply and demand for cars from a homogeneous fleet at

the nodes of a carrier's network are used in a linear transportation program minimizing the total transit time (in car-hours) to find optimal car movements. Cars in surplus of known demands, if any, are prepositioned based on the probabilities that various net demands will occur. This is accomplished by a stochastic L.P. model that minimizes total expected transit time given the demand distribution at each node. The two optimization programs are linked and driven by a simulation model which generates car supply and demand from known distributions derived from historic data, keeps track of and executes the car movements, and modifies and updates car supply and demand at the nodes. The model has been tested on a very small network only and thus the results, although encouraging, are more methodologically than practically interesting. This hybrid approach seems, nevertheless, very promising.

2.2.2 Empty container transportation

Container shipment has become an increasingly popular mode for carrying freight over the past fifteen years. The reasons for the wide use of containers by all modes of transportation were pointed out by Frankel [52] as early as 1968. Not only can containers be used for sea, air, truck or rail transportation, but they also offer the great advantage of easy inter-modal transfers and mixed-mode transportation.

Containers carry obvious advantages of rationalization of shipment, security, facility of handling, multimode transportation. However they pose a number of specific problems such as sizing and management of the fleet, ownership or leasing, multicarrier transportation, fleet pooling and empty container repositioning after and prepositioning before a loaded shipment. The high cost of acquiring, maintaining, handling and transporting containers, make adequate container management a very relevant problem.

Jarke [79], [80] reviews container management problems and insists on the necessity for an efficient information and decision support system for container transportation logistics.

Several authors have addressed the problem of empty container distribution as that of allocating containers available at a surplus terminal from an earlier loaded shipment, to a demanding terminal (e.g. client's warehouse, railroad terminal or port) in preparation for subsequent loaded transports. All these authors take a deterministic approach to the problem, which is essentially dynamic in time, and use classical linear programming formulations.

Potts [118] has solved this problem for the movements of empty containers in Australia using the standard out-of-kilter algorithm.

White [147] discusses various aspects of the empty container distribution problem and adapts to it the earlier work of White and Bomberault [148] on empty freight car transportation. Assuming that the locations at which containers can be positioned, the demand and the time horizon are known, White builds a space-time network referred to as the dynamic transshipment network. The distribution problem is again solved using the out-of-kilter algorithm. The method is illustrated through a small size numerical example.

Ermol'ev, Krivets and Petukhov [40] pose the problem of supplying ports with empty containers in time in preparation for subsequent seaborne shipment. They build a dynamic network model where empty containers will be transported by ship using the loaded container lines. They propose solving the problem by a network optimization algorithm and report some closely related work by Perevezentsev [113].

In his recent doctoral dissertation, Florez [45] reviews extensively the problem of empty seaborne container repositioning and leasing. Based upon the work of White and Bomberault [148] and White [147], Florez

builds a dynamic transshipment network solved using two alternative linear programming algorithms. This is an operational model to be used by the management of a shipping line prior to the departure of every vehicle (vessel, truck, train or barge) from any location in the network (ports and inland terminals). The methodology provides a recommended strategy for that particular departure, including the number of empty units to be loaded aboard the departing vehicle and the number of units to be leased, with time and location recommendations. The model covers a planning horizon defined by the user. The methodology was applied to an actual situation related to the U.S. East Coast-Brazil trade.

It is somewhat surprising to note that, in spite of some very interesting problems with important practical applications, work in empty container allocation has still not integrated the latest methodologies created for the other modes (e.g. rail and truck) and has not yet generated any truly innovative modeling approach.

2.2.3 Rail-multicarrier

The inter-railroad freight car pool concept has received increased attention in recent years, especially in the U.S. where the multiplicity of rail companies and the heaviness of operational and financial rules regulating intercompany car exchanges were significantly contributing to the large number of empty car-miles and costs that the industry has been facing. This concept is based on an agreement between railroads and, possibly, some shippers, that cars be pooled at many loading points and that the cars emptied at destinations can be sent to any loading location. The automobile industry, which was one of the prime supporters of the idea, first started in 1981 to apply the freight car pool concept to finished vehicle shipments from plants to ramps (unloading points) using multilevel rack cars. One automobile company already reports significant empty car

mile reductions (39.5 million car miles, for the 1981 model year, for 13 production plants and 40 rail ramps with 5,500 pooled cars) as compared to the traditional method (Association of American Railroads [3]). Note that vehicle pooling between carriers is also found in the container transportation industry (Dejax, Durand and Servant [37]).

Linear programming is the main methodology for the allocation models used in these projects (Association of American Railroads [3]). Several research efforts have recently been devoted to the improvement of this methodology.

Kikuchi [91] proposes a model for a homogeneous fleet of pooled cars, continuously and centrally monitored and dispatched. Reasonable forecasts of supplies (from the central monitoring system) and demands (from shippers) are assumed known. The objective of the model is to develop daily dispatching instructions for each car in the system so as to minimize the total costs of car storage, travel and shortage penalties for the analysis period. The model is formulated as a linear transshipment problem over a space-time network where arcs are used to indicate car holdings and movements. The model should cover a long enough period to allow completion of travel between various locations but would normally be run daily with updated data. Kikuchi presents limited computational results, mainly to illustrate on a very small network how cost matrices have to be computed.

Glickman and Sherali [58] address the same problem except that they take into account different car types with limited substitution. Their approach is different, however, in that they develop several models, each aimed at finding the optimal distribution of the empty pooled cars from a different viewpoint. The first system model simply minimizes the total cost of distributing and interchanging the pool of empty cars. It is formulated as a classical transportation problem obtained from a space-time network (transshipment) problem incorporating shortage arcs. A second

system model aims at improving the balance of relative benefits among the railroads according to a designated criterion while staying within a specified range of the optimum of the first model. The third, "company focussed" model minimizes the total cost subject to prior standards placed on the benefits that the distribution and interchange of cars give to each company. Comparison of the solutions of the models permits an estimation of the cost of meeting the objectives of each railroad. A modified large-scale network optimization code (NETFLO, see Kennington and Helgason [88]) is used to solve the transportation problem. The other models are solved using the Dantzig-Wolfe decomposition algorithm [96] using the network code for the subproblems and a heuristic rounding procedure to obtain integer answers. Glickman and Sherali present application results using actual operating data and report successful applications to the distribution of covered cars for fertilizer, grain and insulated boxcars for beer.

2.3 Combined empty and loaded vehicle allocation

Demand for empty movements arises from unbalanced loaded movements. It is thus natural at the operational level to try to integrate the two types of movements into a single vehicle allocation-dispatching model.

2.3.1 The rail case

Gorenstein, Poley and White [62] propose a computerized car-move scheduling process, to be embedded within a real-time control system, meant to improve equipment utilization and customer service. The scheduling system is composed of an empty car allocation model similar to that of White and Bomberault [148] and a complete traffic scheduling model which is an L.P. multicommodity minimum cost formulation on the network defined by the yard classification policies and the train schedule. The empty vehicle allocation problem considers a homogeneous fleet of cars only. The authors acknowledge the impact that different types of cars and their interrela-

tions may have on the solution and suggest that, in the context of the proposed system, it may be appropriate to pro-rate the interdependencies and then examine each fleet separately. No implementation is mentioned nor are any results presented.

In his Ph.D. dissertation, Shan [135] develops two models aimed at improving freight car utilization and providing an analysis tool for problems arising from the sharing of cars among railroads. The first model treats the homogeneous fleet case as a transshipment problem on a space-time network. The second formulation distinguishes several classes of cars and is formulated as a capacitated network minimum cost flow problem. A set of network simplex algorithms is used to solve the two formulations. Note that the models are embedded into an interactive computer graphic system. Encouraging experimental results are reported on several hypothetical case studies.

Kornhauser and Adamidou [92] view the freight car management problem in the U.S. context as an N-person non cooperative game formulated as a multicommodity flow problem on space-time networks representing the managerial options of each railroad : hold, ship empty or loaded inside or outside the company's network. The problem is solved by an iterative heuristic that cynically solves each problem until equilibrium is obtained for the coupling variables. Two and three railroad examples are solved. Although theoretically interesting, this approach does not seem to be practical for real cases, due to the very rapid growth of the problem dimensions and of solution times with the number of participating railroads.

Haghani and Daskin [65] propose a combined model of train routing and empty car allocation built on a time-space network that accounts for yard operations and train movements between yards (see Haghani [64] for a detailed presentation of the model and solution procedure). The resulting nonlinear mixed-integer formulation is solved using a heuristic procedure that first decomposes the problem into temporal stages, in turn decomposed into a car and an engine flow subproblems. The operational treatment of

what is essentially a tactical/strategic problem (see section 4.1) creates, however, a number of problems. First, the size of the problems are severely limited by the dimensional explosion of the space-time network (the authors report experimental results on a four node, five two-way links, three day problem). Furthermore, the range of problems that can be treated is also very restricted : simple routing (yard to yard direct trains) possibilities, no link congestion, one product, one train type, etc. Yet, integrating empty flows considerations into larger planning models is an important objective and Haghani and Daskin's work is a worthwhile effort in this direction.

2.3.2 The motor carrier case

Research in vehicle allocation problems for motor carrier transportation is relatively young and, as such, has been able to bypass some of the stages experienced for the other modes, especially rail. Thus, although some models of this type are owned and used by some motor carrier companies ([122]) to our knowledge no papers in the literature present the empty truck allocation problem in the now classical formulation of a linear transportation or transshipment model over a dynamic or static network. In fact, the state of the art for the vehicle allocation problem for the truckload motor carrier is the stochastic model with a dynamic (explicit or implicit) network structure.

It is interesting to note that the "less-than-truckload" situation has been mostly addressed at the tactical and strategic levels (see section 4.1). The models for the truckload case follow and generalize the earlier work of Jordan and Turnquist ([83], [86], [141] — see section 2.2.1) in the context of the rail car distribution problem. Important differences between the two modes have, however, influenced the research effort. Most influential, probably, is the fact that a truck may be loaded several times within the operational planning horizon. This implies that both loaded and

empty movements have to be considered and also that random demand has to be accompanied by random supplies. On the other hand, truck travel times are more stable and stochasticity is less of a problem here.

Powell, Sheffi and Thiriez [126] describe a model which aims to allocate the trucks of a homogeneous fleet to the nodes-regions of a space-time network so as to maximize the net expected revenue. The demand forecasts are random variables with known means and variances from Erlang distributions. The supplies of trucks are, however, assumed deterministic. The resulting model is a nonlinear (concave) network optimization problem. The authors present two equivalent formulations of the model and derive corresponding solutions algorithms based on the Frank-Wolfe approach. In both formulations the decisions variables are the (random) flows of vehicles moving between pairs of regions over time. Numerical results are presented using a network of a medium size trucking company with national coverage in the United States (40 regions, 295 nodes, 4840 links).

The preceding model supposes that of the vehicles moved between two regions in a period, as many as possible will move loaded. Also, if external supplies at nodes are deterministic so are the interregional arc flows. But, as Powell [120] notes, in reality a truck will be moved only if it can be moved full, which implies that the model will generate more empty travel than necessary. Powell then presents an extension of the previous model where demand and exogenous supplies are random independent variables described by Erlang distributions with known parameters. The model distinguishes between vehicles that may move if they are full and vehicles that move empty. Trucks allocated to full movements but in excess of actual demand are assumed to be held over in the same region until the next time period. The model is formulated as a nonlinear non-separable problem (concavity is not yet proven) with a simple constraint structure well

suited to the application of the Frank-Wolfe algorithm. Numerical experiments are presented suggesting very good computational efficiency, partially due to a very efficient adaptation of the Frank-Wolfe method.

A limitation of the model is the assumption that all vehicles allocated to loaded movements but in excess of actual demand are kept in the originating region. In fact, if a vehicle many not be used on one link, it may be used on any of a number of other links. Also, the solutions of this model, as well as those of the previous one, are no longer integer, a somewhat disturbing characteristic in a real time decision environment.

Powell [121] then presents an alternative model that can be used in a real time environment to decide, under uncertainty, how to allocate a homogeneous fleet of vehicles while anticipating the future consequences of present decisions. Powell returns to the dynamic network formulation, which allows the utilization of very efficient algorithms and guarantees integer solutions. The innovative aspect is that the network is part deterministic, part stochastic. Deterministic arcs (generally emanating from regions-nodes in the first time period) represent the known movements, loaded and empty, of the first dispatch of the vehicles with known costs and revenues. Stochastic arcs, emanating from all nodes at each point in time and ending at a sink node at the end of the planning period, represent uncertain information : the second dispatch of the (empty) vehicle to some uncertain load, as well as the set of movements beginning with the third dispatch until the end of the planning horizon. The costs or these arcs represent the total relative value of each vehicle sent to a region and include the expected earnings of the vehicle for the second, third, and following dispatches, until the end of the planning horizon. These costs are computed by a "regional impact model" which estimates expected revenue values based on forecasted values of empty and loaded future movements (using time series models and Poisson distribution fitting) and on dis-

patch probabilities computed by distribution convolution techniques. These computations also depend on the average value an additional vehicle in a region will contribute from a particular point in time until the end of the planning horizon, called regional end effects, computed by Markovian techniques. A real time dispatching system using this approach has been developed and successfully implemented at a major U.S. truckload carrier. The system has been in actual operation for more than a year now and has generated significant improvements in both the carrier's operation cost and service quality (Powell et al. [127]).

This model constitutes a significant contribution to the field, one that opens up interesting perspectives both for research and applications. It also underlines the requirements for a large and diverse body of data, as well as for reliable forecasting, estimation and validation methods.

To close this section, it is worth mentioning the work of Hughes and Powell [78] on the distortions introduced in dynamic network vehicle allocation models by employing finite planning horizons.

2.3.3 Backhauling

Routing and scheduling of vehicles and crews probably represent the most extensively studied subject on moving goods by truck in the operations research and transportation modeling literature. Bodin et al. [10] review exhaustively the literature on the vehicle routing problem (VRP), or how to route vehicles to visit customers at minimum cost for pick-up and/or delivery. Routing models evidently aim, explicitly or implicitly, at maximizing truck utilization and thus, minimizing empty travel. However, it is not within the purpose of this review to address such models and we refer the reader to the aforementioned paper by Bodin et al.

There are specific situations, however, where empty trips of noticeable importance exist. This is, for example, the case of return trips

after delivering full loads far away from a truck home terminal. One way to reduce such empty truck-miles, is to have drivers haul loads on their return trip toward their home terminal. This is called "backhauling". Regulatory laws of the trucking industry as well as driver work rules and equipment maintenance procedures have long prevented such possibilities. Recent deregulation of the trucking industry, especially in the U.S., has expanded backhaul opportunities. See, for example, Dart [28] for the food industry.

In their report, Cundill and Hull [26] were among the first to address the problem of empty freight truck travel. They claim that about one third of all freight travel is empty and describe three studies, conducted in Great Britain, on why so much empty running takes place : Atkins Planning [4], Wilbur Smith and Associates and P.E. Consulting Group Ltd [149] and the Department of the Environment study. Cundill and Hull analyze vehicle operations, examine the economics of return loading (backhauling) and attempt to assess how much empty running might be consequently reduced. A number of suggestions are made to increase the amounts of backhauling, based on improved communications between customers and vehicle operators and the provisions of guarantees to protect the parties involved by backhauling. The analysis is conducted by building a simple model of loaded and empty travel and applying it to nationally representative traffic data to estimate the possible benefits of an increase in backhauling. The model can be operated in two modes. The first one, called "destination matching", tries to match vehicles returning empty to a town on a typical weekday with loads brought into the same town. The other, called "origin matching", aims at matching empty vehicles leaving a town with loads carried out of that town.

Cundill and Hull conclude that, at least in Great Britain, more than interregional flow imbalances, lack of a proper information system to match

supply and demand for transportation in the very short term and unwillingness by transport operators to carry return loads are significant factors in the high degree of empty travel.

Jordan and Burns [85] examine the impact on backhauling opportunities of truck terminal locations and directional imbalances in the flow of freight and develop a method for determining which truckloads should be backhauled. Backhauling is studied for the simplest case of two terminals sending full truckloads to many customers under steady-state conditions.

Two backhauling models are developed. The first is a continuous model that makes simplifying assumptions about customer locations and travel distances. Such approximate or continuous models provide very useful insights into the nature of the problems and the properties of optimal solutions to more realistic classical models (see, for example, Daganzo and Newell [29]). The model results in formulae showing that savings from backhauling increase at a decreasing rate as the directional flow of freight between two terminals become more balanced and that backhauling is an important, but often ignored, factor in terminal (e.g. trucking terminal, warehouse or plant) location and supplier selection decisions. The second model is a more general discrete model that determines which loads should be backhauled to minimize empty truck-miles. Customers are discretely represented and actual travel distances between each terminal and each customer are used. The backhauling problem is formulated to maximize backhaul savings subject to a load balancing constraint. It is solved by a "greedy" heuristic where each iteration adds the one available customer from each terminal with the maximum backhaul savings to the group of customers served in backhaul loops.

As an extension, Jordan [84] develops a model to help coordinate backhauling between many terminals. Trucks leave their home terminal and deliver their loads to clients. They may then return empty, or drive to a

closer terminal and pick up a backhaul load to be delivered near their home terminal. The model assumes each truck may carry at most one backhaul load before returning to its home terminal. The model is formulated as a matching problem that leads to a heuristic for solving the very large backhauling problems that arise in practise. Using Lagrangian relaxation, another formulation allows a very tight bound for the optimal solution to be calculated. On a large scale example, the heuristic yields a solution within 1% of the optimum. Other extensions of this problem would consider fleet sizes, truck travel and delivery times and specific labor restrictions.

Cundill and Hull [26], as well as Jordan and Burns [85] and Jordan [84], propose to use backhauling opportunities in specific and similar cases : multiple terminal, or town, systems, where trucks carry full loads from their home terminal to a client and may take full loads from another terminal (town) nearby on their return trip, instead of returning empty, as they otherwise would have. In this sense, "backhauling" addresses situations where routes are already established and a load is sought only for their last leg, otherwise travelled empty. Note that, even if in these papers the load is of same nature on both fore and back trips, the term "backhauling" is also used in situations where the loads are of different types : for example, a truck from a less-than- truckload motor carrier used as a full truckload vehicle on its return trip.

2.3.4 Multimode distribution systems

Intermodality is a transportation alternative increasingly chosen nowadays, both by individual shippers and by companies operating large distribution systems, for economic as well as performance reasons. A shipper, however, only has to choose the best itinerary, according to his own criteria, among the services offered by carriers. On the other hand, for a company operating multimodal distribution systems, the problem

becomes that of choosing the shipment mode for each load so as to minimize the total cost of both loaded and empty vehicle movements.

Turnquist and Jordan [145] (see also Jordan, Turnquist and Bustamante [87] and Turnquist and Bustamante [142]) present a model aimed at solving this problem. Their work was initially motivated by the study of the distribution system of a large U.S. automaker, involving the transportation of automobiles from assembly plants to dealers by rail or truck. The authors first formulate the problem as a linear programming model where the loaded flow on every intermodal alternative (only rail-truck combinations are possible at predefined transshipment points) and the empty flows on every mode are considered explicitly. Empty rail cars are sent back to originating plants, while trucks must observe routing restrictions. They then rewrite the model as a nonlinear formulation where the two empty flow problems, obtained by repositioning trucks and cars once a feasible solution is found to the loaded distribution problem, are represented only by the inclusion in the objective of their optimal solutions as functions of the loaded flows. This transformation allows the solution of the problem by a Frank-Wolfe algorithm in which the subproblems are L.P. transportation problems. The authors report good computational results and discuss the use of such combined loaded-empty models in the planning of distribution systems.

Note that this model may be considered either as an operational tool or as a policy model. In the last case, it has to be compared with the service network design models described in section 3.1. An interesting extension would be the relaxation of the very tight restrictions on the type and number of intermodal routes.

3. POLICY MODELS

Empty vehicle transportation problems may not be fully addressed at the operational level only. Empty flows are an important component of

tactical and strategic problems such as national and regional planning, carrier service network design, fleet sizing, logistic system design, etc. Recent reviews by Daskin [30], Turnquist [140], Crainic [17], mention the important role of empty travel in general logistic or transportation problems.

In this section we examine the role and modeling of empty vehicle flows in policy models, either from a strategic or a tactical point of view.

At this point, we want to stress again that, while the present discrimination between policy and operational models does follow a number of well established criteria, the precise classification of each type of model is still very much a matter of personal opinion. For example, the classification of the service network design models as policy models is certainly such a personal choice meant to emphasize their broader scope as compared with the very short term planning models of the previous section.

3.1 Service network design problems

Agencies supplying transportation services in an intercity freight transportation system generally operate complex networks consisting of numerous pick-up/delivery points, large classification/consolidation terminals and either physical (e.g. rail tracks) or conceptual (e.g. road or air lines) links connecting them. One of the main aspects of the decision making process of these agencies is the tactical planning of their operations (design of the service network - routes and level of service, terminal policies - and the routing of traffic through the service network) resulting in what is often called a transportation or load plan (for less-than-truckload - LTL - motor carriers). Crainic [17] gives a thorough review of these models.

Although they are not always present in earlier models, empty flows are given proper consideration in recent formulations.

Powell and Sheffi [123] and Powell [119] propose a network model for the LTL motor carrier load plan problem : what direct interterminal services should be offered and how should traffic be routed to minimize total transportation and handling costs while satisfying level of service requirements for given markets. The problem is formulated as a large mixed integer programming problem solved by a decomposition algorithm that uses a local improvement heuristic for the network design problem and solves the traffic routing and empty balancing problems as subproblems. The empty balancing problem is formulated as a classical linear transshipment problem solved by an efficient network simplex code. It is interesting to note, however, that this approach was found to seriously underestimate the total empty movements by as much as 50% (Powell and Sheffi [124], [125]), due to time- of-the-day and day-of-the-week effects. To counter this tendency, a fixed fraction of each O/D loaded flow was assumed to return empty and was added to the empty surpluses and deficits that were then imputed to the linear formulation.

Powell and Sheffi [124], [125] describe the design and implementation of the model as an interactive-graphic optimization system. The system is presently actively used by a major U.S. motor carrier, resulting in significant improvement in both cost and service efficiency.

Crainic, Ferland and Rousseau [22] propose a network model that integrates the tactical issues (train service and traffic routing decisions, blocking and makeup policies) in rail freight transportation. Its goal is the generation of global strategies to reduce the total operating and delay cost of the system. The model explicitly considers the service frequencies and has the structure of a nonlinear, mixed integer, multimode, multicommodity flow problem (in arc-chain formulation) minimizing an objec-

tive which combines operating costs, delay costs and penalty costs for service or capacity requirements. The O/D empty demand is exogenously computed, empty cars being then considered as another commodity. Crainic and Rousseau [18] describe the general carrier service network design formulation of the model and present a decomposition algorithm used to solve it efficiently.

Roy [130], [131] has successfully adapted this methodology to the LTL trucking problem. He uses the same modeling and algorithmic framework but employs the various delays in terminals and on the roads to compute transportation time means and variances to evaluate, through penalties in the objective function, the service performance on each route as compared with predefined service requirements.

Empty balancing is done once the main algorithms stops, by a linear transportation problem, on a special network. The nodes are the surplus and deficit terminals. For each service, maximum and minimum frequency variations are found and associated marginal costs are computed from the corresponding variations in the value of the global objective. Each service then generates two arcs of the transportation network with capacities and costs equal to the frequency variations and marginal costs respectively. This approach has performed well on real data and may also be used to determine on what routes and at what costs backhaul loads should be accepted. Note that Crainic and Roy's approach is also the core of an interactive-graphic planning system (Crainic and Roy [19]).

It is interesting to note the imaginative ways, found in both preceding methods, of using linear transportation models for empty flow balancing. A comprehensive comparative analysis of the way these methods address the service network design problem is, however, beyond the scope of this review. As both present some very interesting characteristics and

have been successfully applied, we cannot but hope that this analysis will be performed in the near future.

3.2 The estimation of demand

The lack of an appropriate and reliable information system on empty vehicle freight availability and demand is often mentioned as a major problem by researchers as well as by practitioners. Moreover, such information is essential for the proper allocation of traffic as well as for system design purposes.

Transposing the concepts of the estimation of demand for passenger or loaded freight traffic flow problems, three different issues may be considered :

- the estimation of availability of empty vehicles at origins; this may result from previous loaded shipments or from exogeneous supplies;
- the determination of needs for empty vehicles at destination points for subsequent loaded shipment or any other operation;
- the forecasting of empty flows between specified origin and destination pairs.

The first two problems are similar to that of forecasting passenger or freight volumes at origins and destinations in other transportation planning problems. An accurate estimation of the supply and demand for empty vehicles is a necessary input for vehicle allocation models (see section 2) as well as for the strategic and tactical planning models presented in this section.

The third problem corresponds to the estimation of origin-destination matrices and is necessary, either per se, or combined with origin-destination matrices of loaded freight flows, for national or regional strategic freight transportation planning, as well as for an adequate tactical organization of carrier operations.

It is also noteworthy that the estimation of empty vehicle supply and demand cannot be simply derived from loaded movements : several other factors must be considered, such as repairs, discharge, new car inputs, carrier pooling and renting. To our knowledge however, very little work has been specifically done relative to the empty vehicle demand estimation problem. Supply and demand are often estimated from statistical analyses of observed loaded or empty flows (see Powell [121], or Dejax, Durand and Servant [37]).

We know of only two specialized models for the estimation of the demand for empty freight vehicle transportation. These models are conceptually straightforward and readily applicable. More research should certainly be undertaken in this area.

In his master's thesis, Coutu [14] applied the gravity model to the prediction of flows of empty rail cars. Recall that in the gravity model, the flow between an origin- destination pair is assumed to be proportional to the supply at the origin and the demand at the extremity; the proportionality factor depends on parameters such as distance and the cost of travel between the two points. Coutu's work describes concretely the steps to be taken in applying this kind of methodology to the prediction of empty rail car traffic, with the Canadian National Railroads (CNR) as a case study. The CNR transportation department needs such forecasts to plan the allocation of resources in order to satisfy the demand for both loaded and empty movements at all nodes of the network. The gravity model was applied and calibrated according to the techniques proposed by Evans and Kirby [41] and gave satisfying results for this particular application.

Hautzinger [72] proposes a very simple and readily applicable model for the combined prediction of loaded and empty interregional freight vehicle flows. It is specialized to truck transportation between two cities but could be generalized to more complicated cases. The model, which is

explained in greater detail in Kessel et al. [89], [90], is based on simple and realistic hypotheses about loaded and empty trips related to carrier base location, distance, demand, and total flow equilibrium.

In section 3.4 we describe how some of these demand estimation models have been integrated into network equilibrium models for the more general problem of predicting intercity freight flows.

3.3 Fleet sizing models

Fleet sizing models usually deal with the following problem : given the demand for loaded trips (number of trips leaving each node of the network) and the characteristics of each trip (length, uncertainty, etc.), what optimal number of vehicles is needed to satisfy demand with respect to some criterion (often, the minimization of total cost). Only recently have researchers manifested a specific interest in the empty vehicle factor in fleet sizing problems. As reflected in the literature, these problems also cover inter-carrier cooperation and vehicle-pooling problems.

A convenient way to avoid fleet sizing problems is to use a fleet of leased vehicles as needed. Golden et al. [61] propose such a model for the routing of vehicles. Ball et al. [6] address the problem of truck fleet sizing in the presence of a common carrier option.

Turnquist [140] reviews several papers on the fleet sizing problem in general. He concludes that there are important problems to be solved, with several ways of trying to address them and that it is not obvious which approach will yield the best results. He proposes a taxonomy of vehicle fleet sizing problems distinguishing deterministic and stochastic models : one-to-one (single origin to single destination); one-to-many (most classical vehicle routing problems from a single depot to serve a set of customers) and many-to-many problems; full or partially loaded vehicle problems.

Turnquist and Jordan [144] develop a model for sizing a fleet of containers used to ship parts from a single manufacturing plant to a group of assembly plants. Parts are produced in a deterministic production cycle but container travel times are stochastic. Based on results for an infinite-channel service process, the authors derive equations relating fleet size to the probability of container shortage. An example illustrates this fleet size-shortage probability trade-off and shows the impact of the uncertainty level and the number of plants on the size of the fleet.

An important potential effect of the improved distribution of empty vehicles is to allow reductions in fleet size without degrading service quality. Beaujon and Turnquist [8] formulate a model which includes the interactions of fleet size, loaded movements and empty movements. It is a stochastic (demand and travel times) optimization model over a dynamic network that is solved by a decomposition procedure that treats alternatively the net inventory and vehicle allocation subproblems. This approach has yielded interesting results on a small example, especially concerning the role of uncertainities and dynamic factors in empty vehicle allocation and fleet sizing problems.

Cooperation and pooling between carriers is often viewed as a means of reducing vehicle fleet size, by improving empty vehicle utilization. The U.S. freight railroad system is made up of many independent railroads and Muehlke [109] mentions that most freight cars are loaded on one railroad and unloaded onto another. The question of how to use the originating railroad's car once it has become empty is a very complex issue. Traditional solutions have been based only on the amount of money received from other railroads for the time one's own cars are in use by those railroads. Marketing strategies have also stressed the value of placing for loading only those cars with the originating carrier's marks.

According to Muehlke, the result of this and similar strategies has been a gross underutilization of and an excessive investment in freight cars. To show the underlying reasons for certain inefficiencies in traditional practices by individual railroads, he builds a simple but realistic two-railroad model. The model shows that cooperative efforts among railroads are necessary if an individual railroad is to improve the level of service to shippers and reduce costs. A better use of existing freight cars will reduce future ownership and present operating costs for all railroads concerned.

3.4 Prediction of intercity freight flows

Intercity freight transportation encompasses many problems and involves many actors with different means and objectives. Several products and modes of transportation are usually considered, and decisions must be made concerning network and service design, service levels, freight itineraries, flows, prices and market shares. This area also intersects other domains such as marketing, production planning, facility location, physical distribution, logistics, and national and regional planning.

Empty flows are, however, often simply treated, if not ignored altogether, in models to predict intercity freight flows. There are, however, a few exceptions.

A first major class of formulation quite widely used to predict freight flows from regional supply and demand, commodity prices and transportation costs is made up of the so-called spatial price equilibrium models. Harker [69] reviews certain studies that use this approach, and that are also usually considered as demand estimation models (see section 3.2). To our knowledge, none of these models have so far explicitly considered empty movements.

The second major class of predictive freight flow models is made up of freight network equilibrium models. In these formulations, intercity freight movements through a multimodal network are the result of the behaviour of and interactions between service supply (carriers and intercarrier relationships) and demand for transportation (shippers). Friesz, Tobin and Harker [54] and Crainic [17] review this class of models.

Attempts have also been made to integrate network models and demand models : Kresge and Roberts [94], Harker [68], Harker and Friesz [70], Fisk [44], etc. Crainic [17] also reviews these models.

Empty flows are generally not considered in these formulations, or are simply added up as return flows on the same routes of the same values as the forehaul trips (Kresge and Roberts [94], Friesz, Gottfried and Morlok [55]).

A notable exception to this trend is the multimode, multiproduct national strategic planning model of Florian et al. [48] (see also, Crainic, Florian and Guélat [23], [24]. The model, embedded into an interactive-graphic planning tool called STAN (Florian et al. [47]), aims to evaluate the impact of strategic scenarios (e.g., large variations in the composition or value of the demand, policy changes, infrastructure investments, etc.) on the utilization of the national freight transportation system. For STAN, the gravity modeling approach (see section 3.2) has been adapted (Crainic, Florian and Leal [25]) to evaluate, from the O/D demand for loaded traffic, an O/D demand matrix for empty movements on the rail mode. Empties are then considered just as another product to be transported, thus contributing to congestion and costs on rail.

3.4 Logistics System Design

Operational models for empty vehicle allocation as well as most

policy models rely on a network structure for the distribution system. They usually assume this structure to either be imposed by the physical system or to have been determined through earlier studies of distribution network design and facility location.

Network design problems are discussed in section 3.1 of this paper. Facility location for distribution system planning is concerned with the determination of the number, size, location and service area of storage, handling, transportation and routing terminals in such systems. These facilities may be industrial plants, distribution centers, warehouses, depots or ports.

A vast amount of literature has been devoted to the problem of facility location, from two main perspectives :

- modeling and algorithmic research : from the early but often quoted work on heuristics for warehouse location of Kuehn and Hamburger [95] to the most recent research on multicommodity dynamic facility location of Law, Khumalawa and Loh [97], a very large number of papers have been devoted to all aspects of the problem; see also Daganzo and Newell [29] for continuous modeling approximate methods and Cornuejols, Fisher and Nemhauser [15] for a study on the interrelations between heuristics and exact methods.
- methodological studies; see, for example, Geoffrion and Powers [56], or Dejax [35] or Dejax and Turri [39].

Reviews of location models may be found in Handler and Mirchandani [67], Tansel, Francis and Lowe [138], Krarup and Pruzan [93].

Note, however, that the research on facility location, like the routing and scheduling of vehicles, is most often devoted to the storage and distribution of freight and the transportation of loaded vehicles only.

There are several reasons for this lack of interest in empty vehicle issues in location problems. The first reason is historic. While so much work remained to be done to assist freight distribution, the repositioning and dispatching of empty vehicles seemed to be a marginal problem. The cost of empty car movements or return trips was usually accounted for in one way or another in the cost of loaded trips. In the case of rail transportation for example, Davis [31] proposes a method for allocating empty trip costs to loaded trips. This method, accurate for economic decisions, is based on the computation of the opportunity costs of having empty cars available for loading at terminal locations.

Another reason is that the locational issue is actually irrelevant in many empty vehicle transportation problems. Freight terminals are often imposed by the nature of the system : ports for seaborne container ground transportation, railroad freight terminals for empty wagon distribution, plant warehouses for interplant freight transportation. White [147] notes that "the locations at which containers can be positioned will be considered as given".

However, locational problems tend to become an important issue in the design of efficient transportation systems. One of the two major conclusions of Jordan and Burns [85] is that truck "backhauling is an important, but often ignored factor in terminal location and supplier selection decisions". Their approximation formulae show that a trade-off exists between loaded and empty miles which depends on terminal location. Moreover, it has been acknowledged (Boyce [12]) that a major opportunity now exists for the redesign of entire freight transportation systems, as a result of deregulatory policies and significant advances in computer and communication technology.

Locational problems basically rely on a trade-off between so-called fixed costs, associated with the opening or operating of a facility, and so

called variable costs or allocation costs, reflecting the charge of servicing a given customer through a given facility. In many distribution problems, such as empty containers or rail cars, many of the facilities are assumed open for various reasons : they exist already and the investment for opening them is long paid for; they serve other purposes (ports, railroad terminals); their fixed cost is small comparatively to transportation costs because of the first two reasons and because of the railroad pricing mechanism that, somewhat arbitrarily, carries a heavy variable cost.

However, closer study of the trade-offs between the various costs incurred by a distribution system, such as transportation versus inventory costs, suggests that the use of all system facilities for empty vehicle management purposes should be investigated further. Knowing the consequences of the number of storage facilities used on the safety stock of a given inventory, we feel that an interesting extension of the work of Mendiratta and Turnquist [105] would be to study the sensitivity of the system to the number and location of railroad terminals actually used for the storage of empty cars.

Assad [1] reviews different factors influencing railroad facility location and installment and refers to earlier work in this area.

Regarding the ground transportation of vehicles for overseas shipment, Dejax, Durand and Servant [37] and Dejax and Servant [38], propose a planning model for the transportation of loaded containers from port to client for imports, and from client to port for exports and for the transportation, storage and reallocation to clients of empty containers. They designed three submodels and applied them to a large scale European project. The first submodel optimizes the transportation of loaded containers for import and export. The second is a warehouse location model for the collection and redistribution of empty containers within logistics zones. The third is a multiproduct transportation model among warehouses

designed to handle the regional imbalances of empty containers between logistics zones in net-importing and net-exporting regions. The main conclusion is that one could gain by limiting the warehouses specifically used for the storage and distribution of empty containers to a number of inland terminals in addition to the ports.

Crainic, Dejax and Delorme [20] extend this work by proposing a general multiproduct, multimode warehouse location model with equilibrium constraints. Their model essentially combines the two empty container distribution and regional reequilibration submodels described above into one general allocation/distribution formulation. The general class of models for this problem and their properties are presented and analysed in (Crainic, Dejax, and Delorme [21]). The integration of loaded transportation into the model is also contemplated. The formulation should be applicable to the planning of loaded as well as empty vehicle warehouse location and distribution systems and to other transportation modes.

4. GENERAL CONCLUSIONS AND RESEARCH DIRECTIONS

We have surveyed empty freight vehicle transportation problems and the various models that have been built to address them. Over the last twenty years, a fairly large number of research efforts have been dedicated to all aspects of this problem, with the largest concentration on operational models for rail freight transportation.

We note also that in recent years, there has been a quickening of pace, a broadening of scope and a rapid evolution of methodology in all research directions in the field. In fact, as often in freight transportation studies and unlike urban passenger research, one cannot really speak of "state of the art" models and techniques : the field is undergoing too rapid an evolution process. General trends may, however, be identified and promising research directions may be suggested.

To begin with, it may be noted that empty flow problems are best addressed, especially at operational levels, as dynamic (several periods) combined loaded and empty flow problems.

Two modeling approaches emerge as preferred formulation vehicles for the allocation/distribution of empty and combined empty and loaded vehicle problems. Deterministic, usually linear, transportation or transshipment, on dynamic (space-time) networks, formulations make up the oldest and still quite widely used approach. Recently, stochastic modeling, with or without an underlying network structure, has emerged as the leading methodology in the field, especially for real time dispatching/allocation problems. Stochasticity may apply either to travel times or to supply and demand estimation.

Deterministic transport models may still be appropriate for situations where, as in the rail mode, travel times between two terminals are of the same magnitude as the length of the planning period. This class of formulations is also very useful for building submodels for more general tactical/strategic planning of transport operations.

More realistic models should, however, be developed, especially for transit times through and in between terminals and in multicarrier situations. This will probably imply non-linearities in the objective functions, pointing, in turn, toward the need to explore and develop efficient algorithms. For multicarrier situations, game theory approaches should be further investigated and developed.

Stochasticity is an important characteristic of transportation systems and a continuous effort should be aimed at improving its modeling and the associated algorithmic techniques. An interesting field, worth further exploration and extension, is the combination of deterministic and stochastic elements (arcs) into a network formulation.

The application of inventory models and techniques to the control of empty vehicle stocks at terminals should be extended to other modes besides rail. Inventory models could possibly also supply a good way to approximate terminal costs for more general tactical/strategic formulations and could also contribute to improved warehouse location models. These avenues are certainly worth exploring.

For all modeling approaches, the consequences of the various formulation hypotheses (e.g. finite number of periods, stochasticity, etc.) should be investigated and quantified.

A constant feature of all models is the express requirement for good information systems and the very accurate estimation of demand and supply. This area is wide open for research that could yield valuable results for models at all levels of decision making.

That empty flows are an important part of more general tactical and strategic problems is now widely recognized. There is still, however, considerable opportunity for research on how to model empty flows for tactical or strategic objectives. Operational models are a good starting point, but some imaginative aggregating and approximating procedures are needed to make them useful in higher planning level models.

We would also like to mention that artificial intelligence methods (e.g. expert systems) might greatly contribute to the improvement of planning techniques. We are aware of research efforts by a European railroad in this direction for the allocation of empty cars. An American motor carrier is also considering artificial intelligence for the routing of empty "pup" trailers to end from breakbulks [122]. But the field is again mostly unknown territory that offers many exciting research opportunities.

To conclude, we should stress that empty flows are best treated, not

only jointly with loaded flows, but also in an integrated, hierarchical way, following the general direction of current logistics and transportation research. At a strategic level, depot location and utilization modes may be studied and broad routing choices may be made. Empty and loaded movements should be considered at a tactical level to build the service network and the transport plan for the next medium-term period. Then, a real time dispatching system could be used to satisfy varying day-to-day demand, while attempting to stay as close as possible to the policies established by the transportation plan.

Such an approach would allow a better representation of and response to the impact and relationships of the empty vehicle management problem to other aspects of the transportation and logistics system.

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